Sapienza Università di Roma
Istituto Nazionale di Fisica Nucleare
Sezione di Roma
Dipartimento di Scienze di Base e Applicate per l'Ingegneria

Research activity at SBAI (Basic and Applied Sciences for Engineering) – Sapienza and INFN-Roma1, and collaborations with other institutes: beam dynamics and collective effects in linear and circular accelerators

M. Migliorati

Group at Department of Basic and Applied Sciences for Engineering

- E. Chiadroni (PA), L. Ficcadenti (INFN-Roma1), M. Migliorati (PA), A. Mostacci (PA), L. Palumbo (PO), M. Petrarca (PA) + PhD and master students + INFN-LNF collaborators (L. Faillace, B. Spataro).
- Our group has a long-standing tradition of work in particle accelerators and collective effects. We have close collaborations with UCLA, CERN, INFN and ENEA.
- We have expertise in:
  - design of devices for Linacs and circular accelerators
  - beam dynamics and development of simulation codes
  - collective effects and electromagnetic beam-environment interactions
  - RF characterization of accelerator devices
  - Laser-plasma acceleration, THz Laser Laboratory
- Here I will focus the presentation on beam dynamics and collective effects.

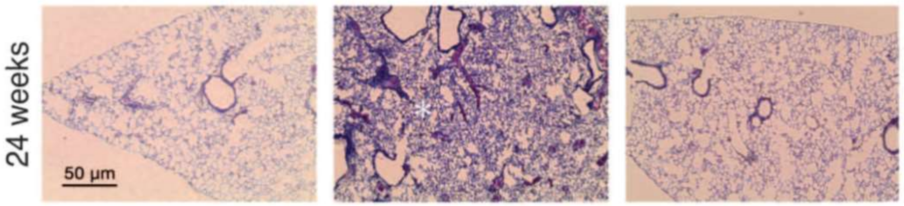
Novel medical linear accelerators for FLASH therapy

FLASH THERAPY is a new method for cancer treatment using Linacs and consisting in delivering very high doses in short time intervals:

- µs pulses of radiation,
- beam-on time < 100-500ms
- high dose per pulse → very high dose rate (>100 Gy/s)

FLASH EFFECT is the improvement of the healthy tissue tolerance to the delivered dose.

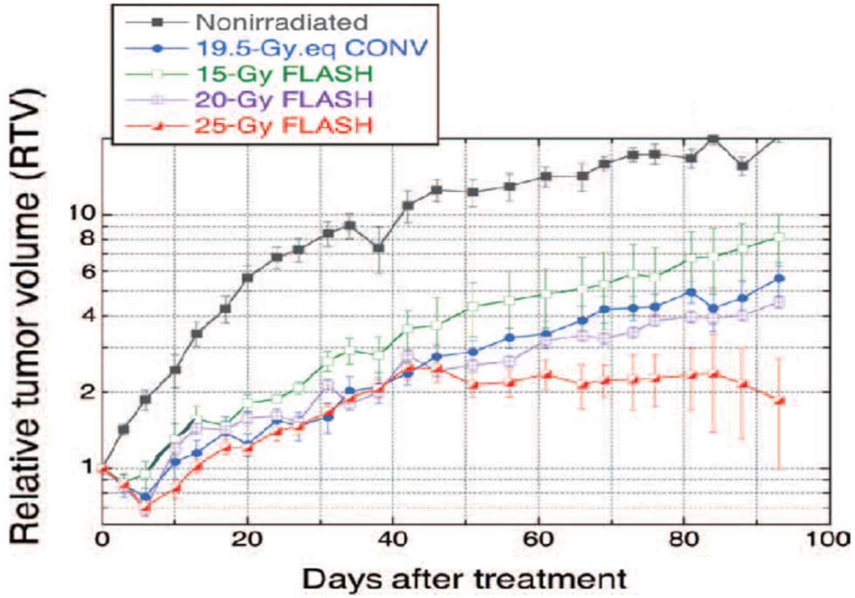
Control 17Gy CONV 17Gy FLASH



Healthy **Fibrosis** **Healthy**

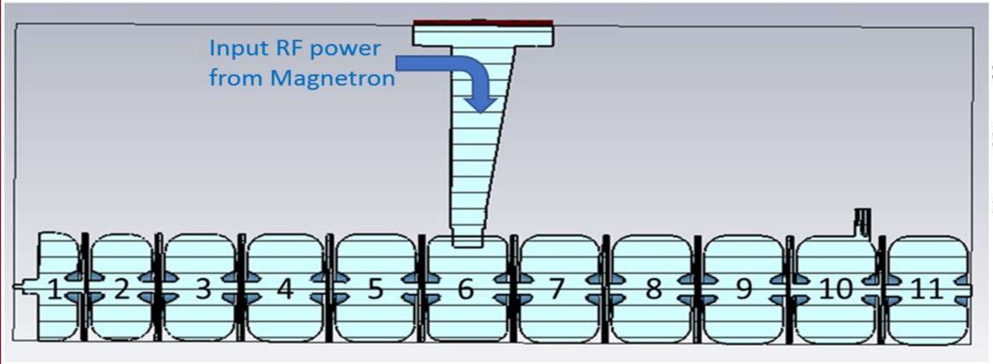
V. Favaudon et al., "Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumour tissue in mice", *Science Translational Medicine* 6, 2014

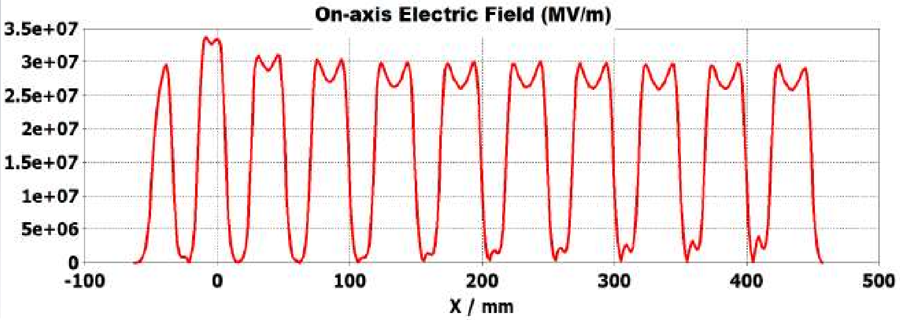
The FLASH therapy is **as efficient as Conventional** irradiation in the repression of tumor growth



Compact S-band linear accelerator

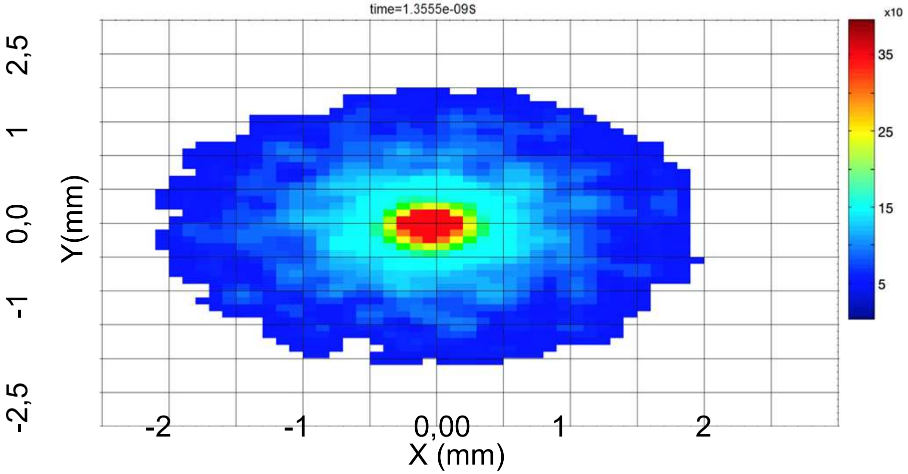
RF design



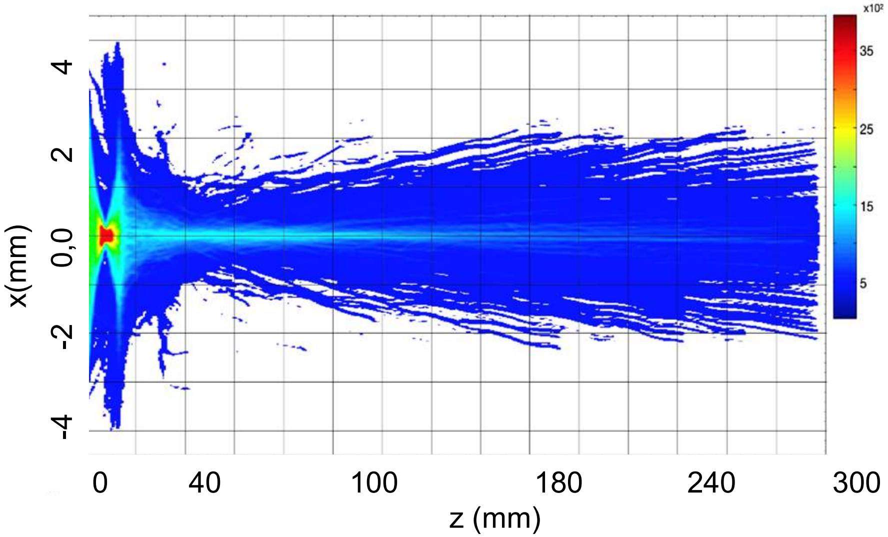


Beam dynamics simulations

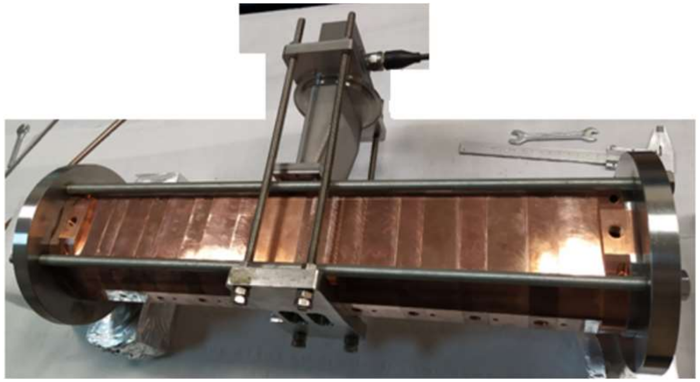
Final beam transverse spot size in cm



Trajectory



Accelerating cells and clamped linac before brazing



Linac installed at Curie Institute

- Variable energy: 5-7 MeV (for other pre-clinical investigations)
- Samples surface variable: 10x10 cm – 4x4cm (high homogeneity for in-vitro screening)
- Target dose per pulse: 5 Gy
- Pulse width: few μs
- Mean Dose rate: 1000 Gy/s
- 10^6 < Dose-rate in pulse:< 10^7 Gy/s
- Pulse repetition frequency: ν= 300Hz

VHEE: Very High Energy Electrons (50-250 MeV) for deep tumors

VHEE & the FRIDA project: a CSN5 call

- FRIDA is a CSN5 interdisciplinary call proposal addressing all the crucial areas related with FLASH therapy. 4 work-packages
- mechanism modelling & rad-bio experiments;
- beam delivery techniques ;
- Detectors for beam monitoring;
- treatment planning development

- The activity of our group is focused on the Linac design. Medical physics topics will be discussed in another talk

UCLA, La Sapienza, LNF-INFN, SLAC, LANL

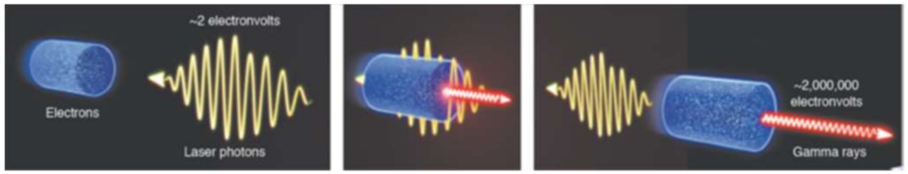
HIGH BRIGHTNESS C-BAND RF PHOTOINJECTORS FOR ELECTRON LINACS

Main Applications and Projects

- High **brightness** (high current, low transverse emittances) electron beams are the key to achieve good performances for advanced radiation sources
- Such beams can be produced by a proper combination of radio frequency (RF) **photoinjectors** and linear accelerators (Linacs) sections

Inverse Compton Sources

- Small footprint facility aimed to produce X/γ **radiation** from electron-photon scattering
- Design based on a **hybrid photoinjector** electron source and a room temperature C-band (5.712 GHz) linac

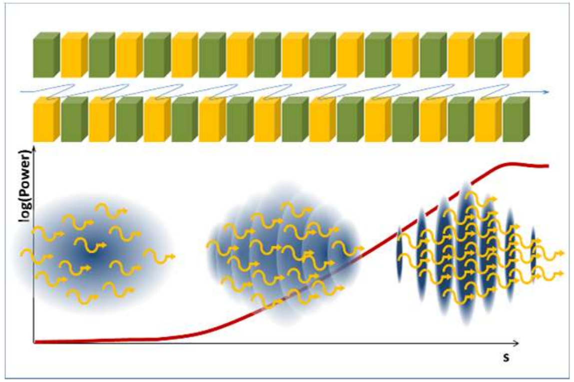


Ultra Compact X-rays Free Electron Laser

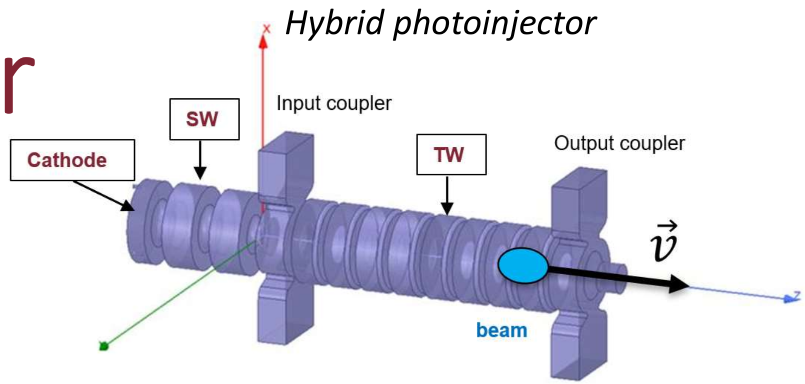
- Compact ($\sim$40 m) facility generating high brightness **X-rays**
- Design based on a high field (240 MV/m) standing wave photoinjector, **cryogenic** (77 K) high gradient RF linacs and **short period** (3 ÷ 6.5 mm) MEMS based undulators

MEMS= Micro-Electro-Mechanical Systems

J. B. Rosenzweig, N. Majernik et alia, “An ultra-compact X-ray free-electron laser,” 2020.

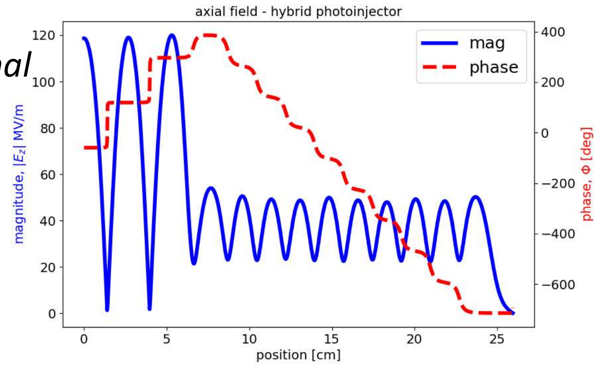


Hybrid RF Photoinjector

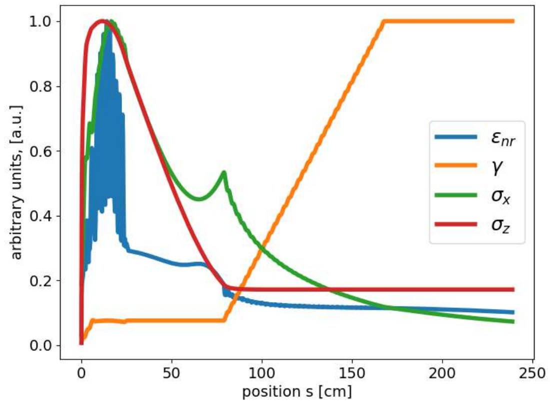


- Multicell RF structure combining a **standing wave** (SW) and a **traveling wave** (TW) section fed from a common coupling cell
- C-band RF design: working frequency is 5.712 GHz
- Electrons are extracted from the **cathode** by an UV laser pulse and are accelerated in the SW region
- The TW structure introduces **velocity bunching** which shortens the beam enhancing the peak current
- A proper combination with solenoid coils and a booster linac allows to achieve **emittance compensation** and velocity bunching together
- The latter results in beams of high **5D brightness** (high current, low emittance)

longitudinal on-axis electric field



Beam distribution moments along a hybrid photoinjector-drift-linac system



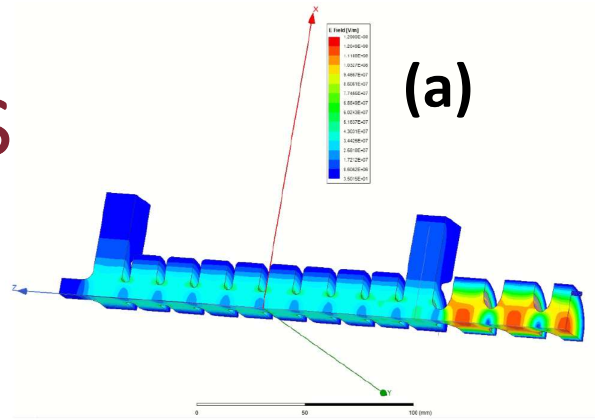
Main Research Activities

Activities concerning the hybrid photoinjector

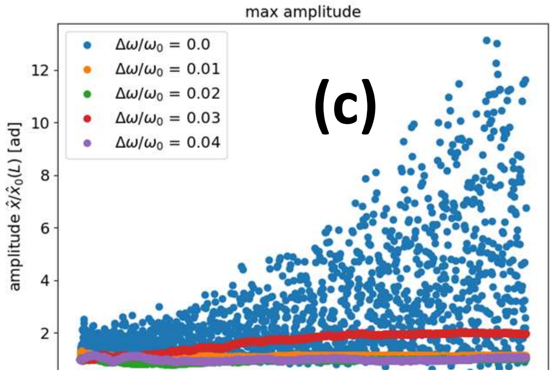
- Design and optimization of the C-band **RF structure (a)**
- Beam **dynamics** studies to achieve the best working point in terms of emittance and peak current **(b)**
- Studies on **instabilities** aimed to keep under control the effects the self-fields generated by the electron beam in the downstream linac sections **(c)**
- Design of the **final focus** optics system for the Compton interaction point **(d)**

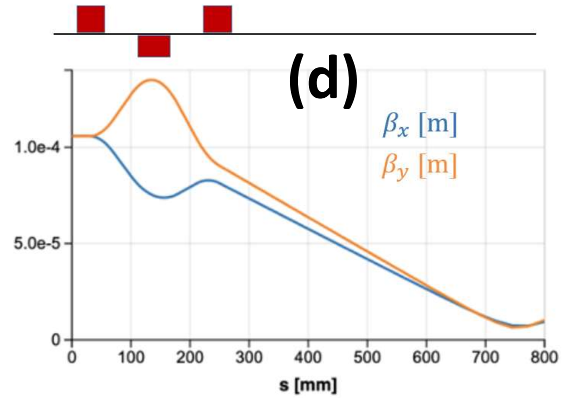
Further applications

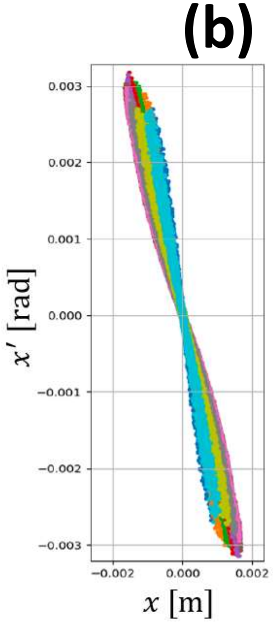
- The good performances shown by hybrid photoinjectors allow to foresee a wide panorama of applications beyond Compton sources
- Hybrid photoinjectors could be employed to drive **FEL radiation** or to fulfill **THz radiation** sources for medical applications



(a) *Electric field*



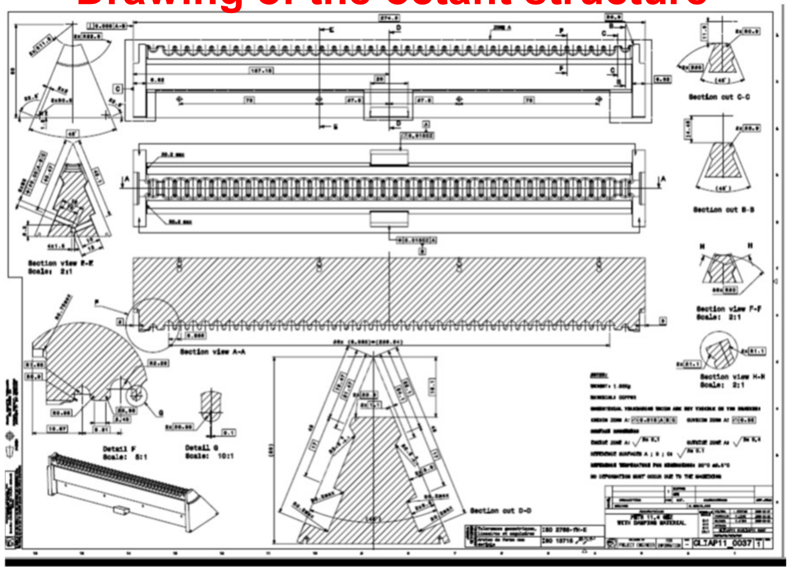


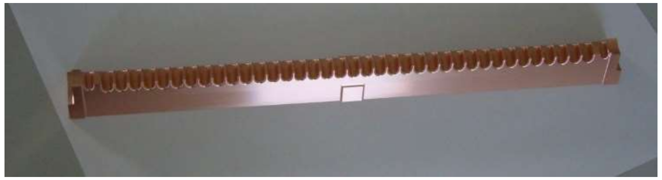


RF technology for ultra-compact, high gradient Linacs

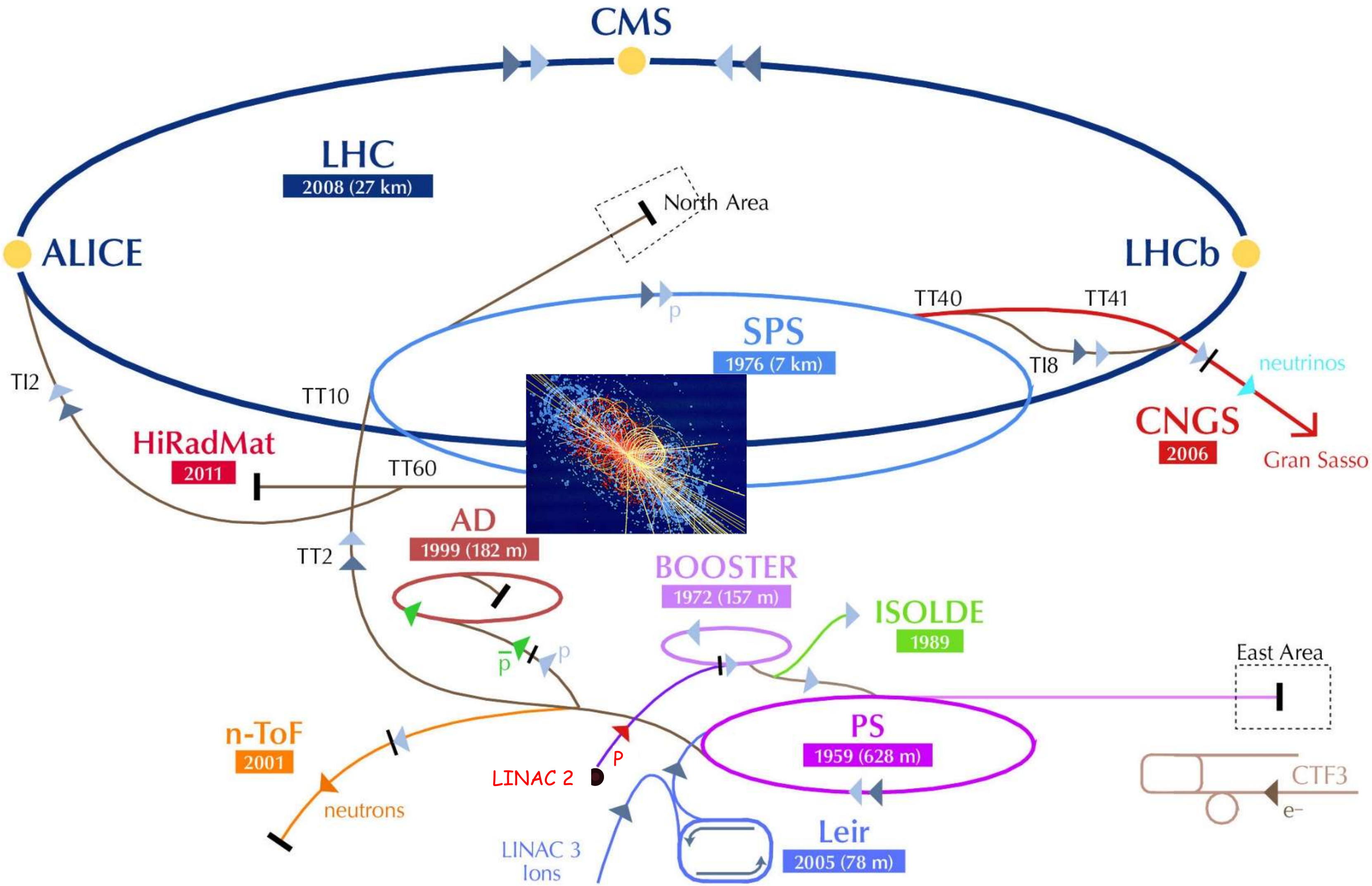
- **Realization of an X-band accelerating structure at high gradient using the jointless 'open structure' technique**

Drawing of the octant structure

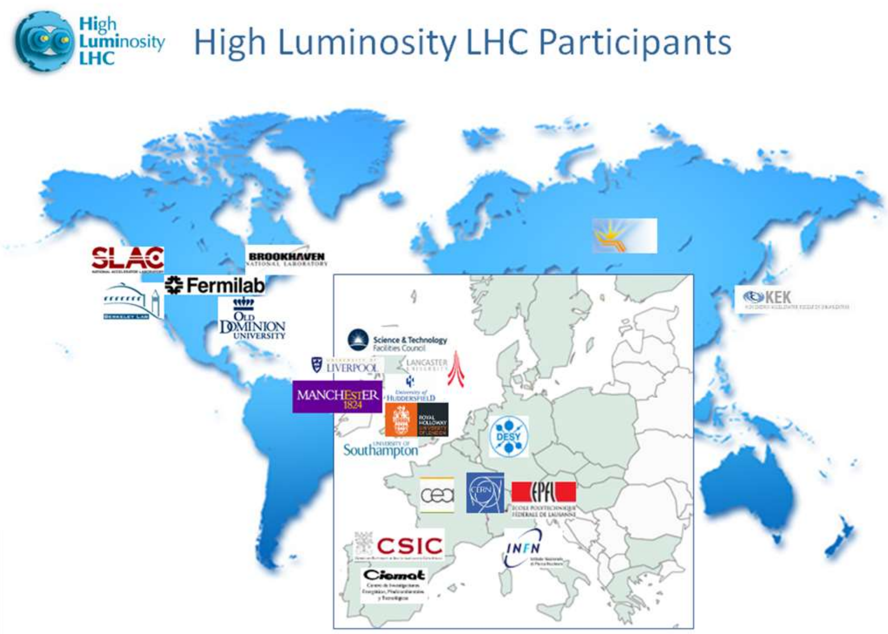


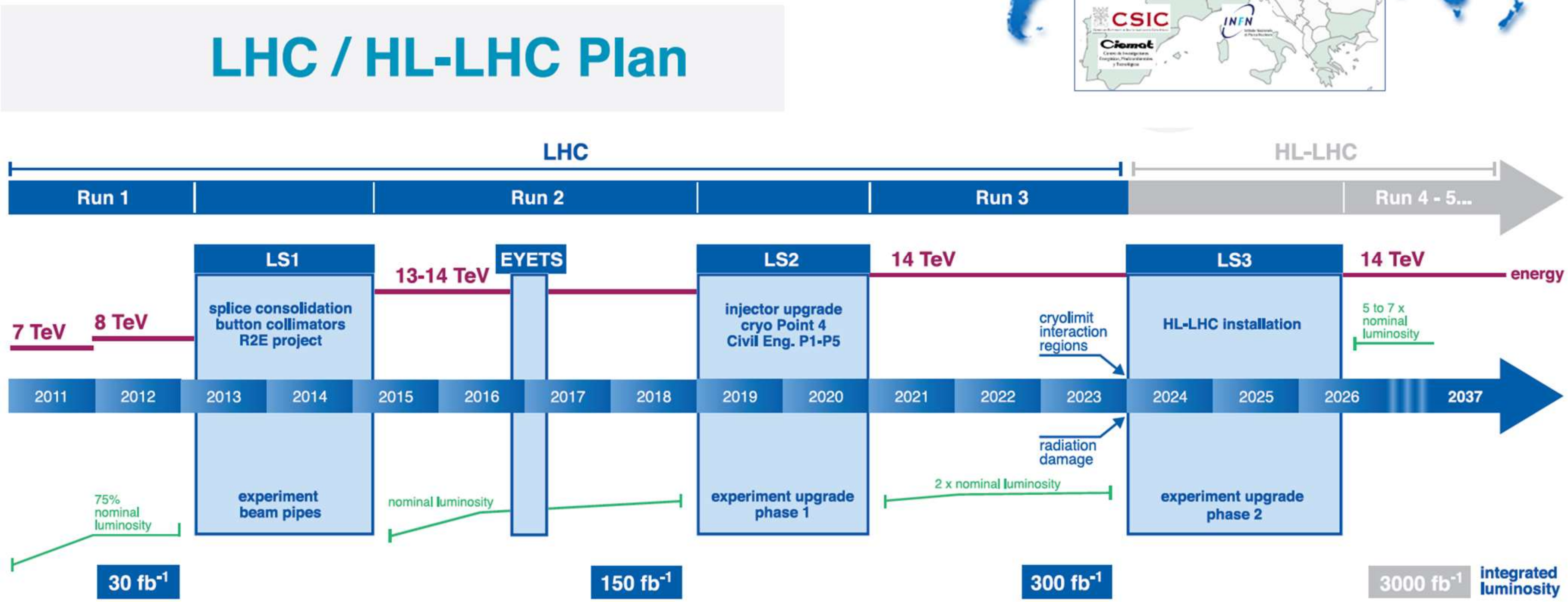


CERN Accelerators Complex

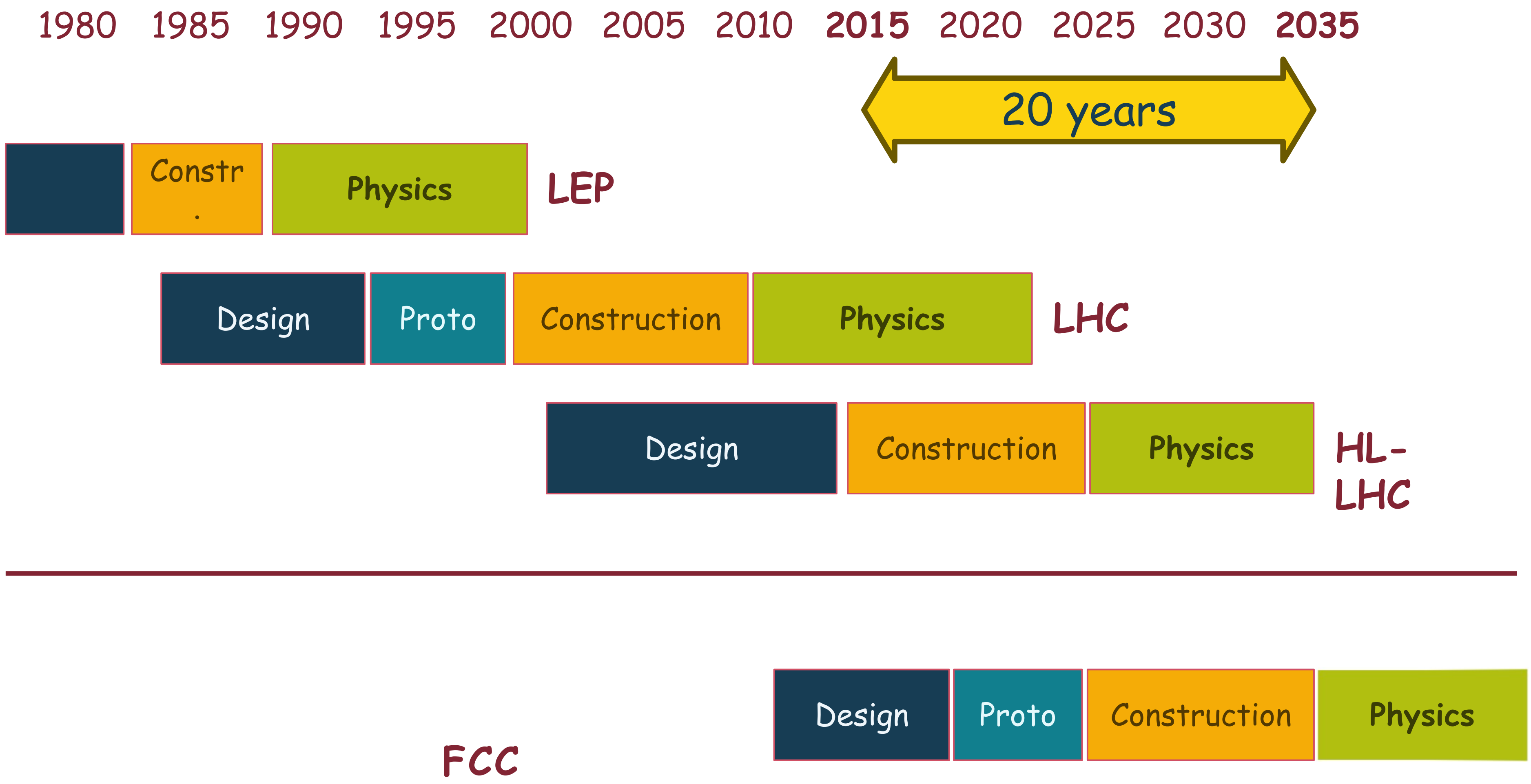


Upgrade of LHC (HL-LHC)





The Future Circular Collider project (FCC)



The Future Circular Collider project (FCC)

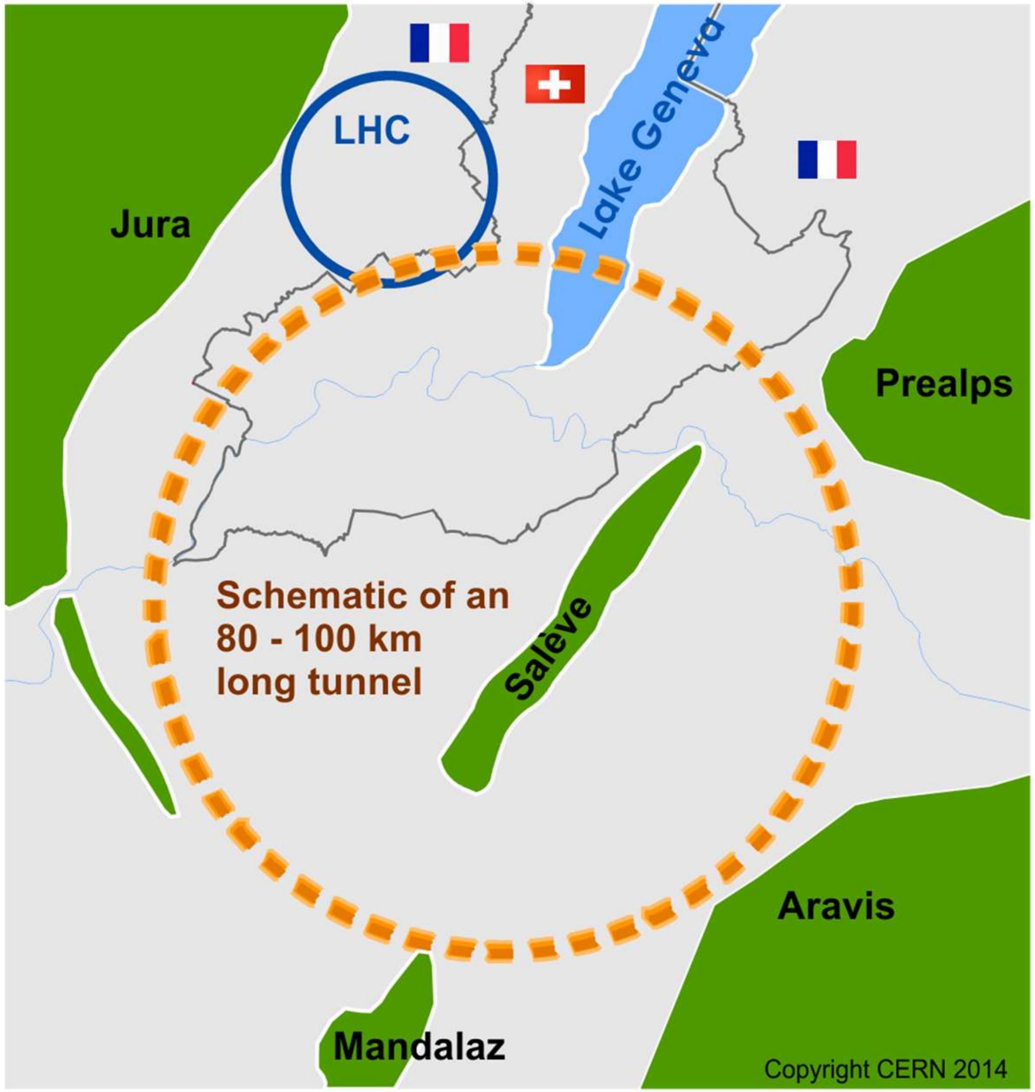
international FCC collaboration to study:

- ***pp*-collider (*FCC-hh*)** → main emphasis, defining infrastructure requirements

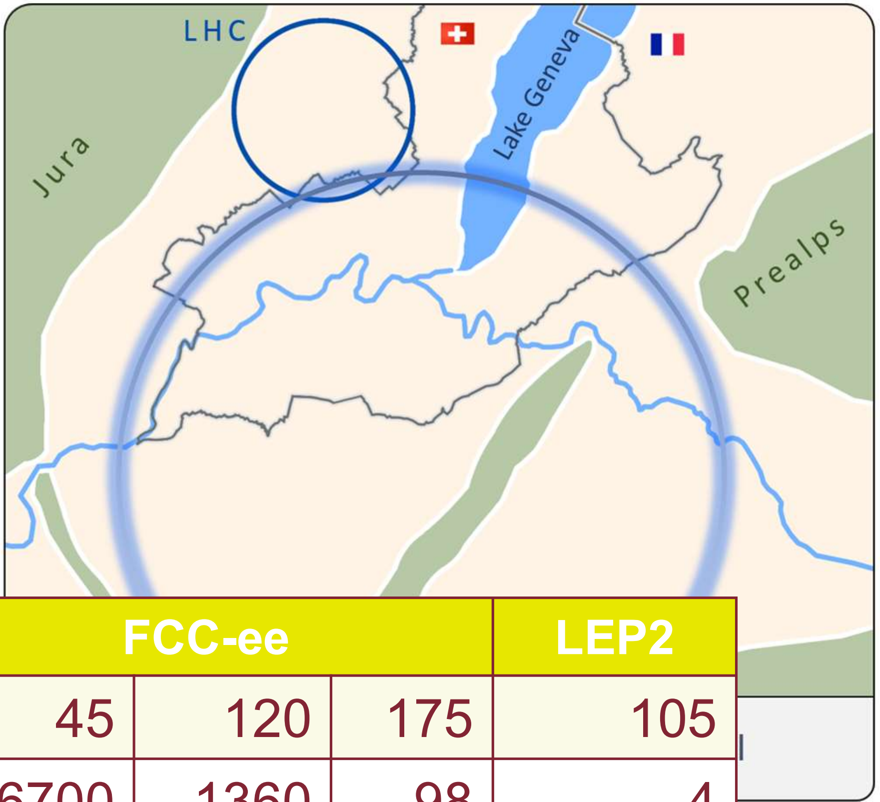
- **80-100 km infrastructure** in

~16 T ⇒ 100 TeV *pp* in 100 km

- ***e⁺e⁻* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**

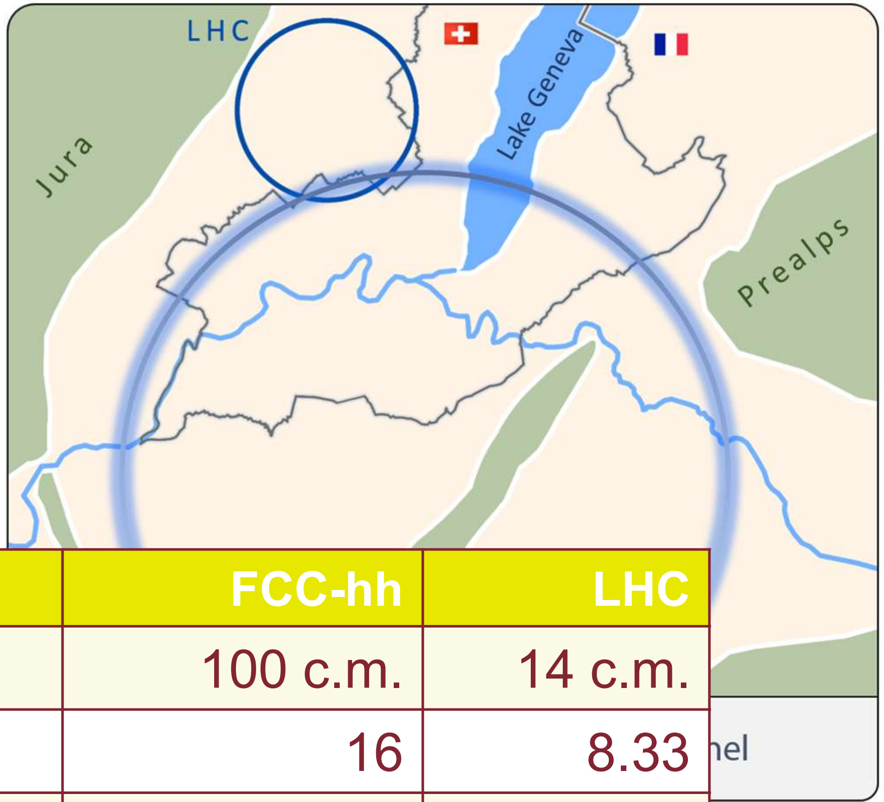


FCC-ee
Key Parameters



Parameter	FCC-ee			LEP2
Energy/beam [GeV]	45	120	175	105
Bunches/beam	16700	1360	98	4
Beam current [mA]	1450	30	6.6	3
Luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	28	6	1.8	0.0012
Energy loss/turn [GeV]	0.03	1.67	7.55	3.34
Synchr. Power [MW]	100			22
RF Voltage [GV]	2.5	5.5	11	3.5

FCC-hh
Key Parameters

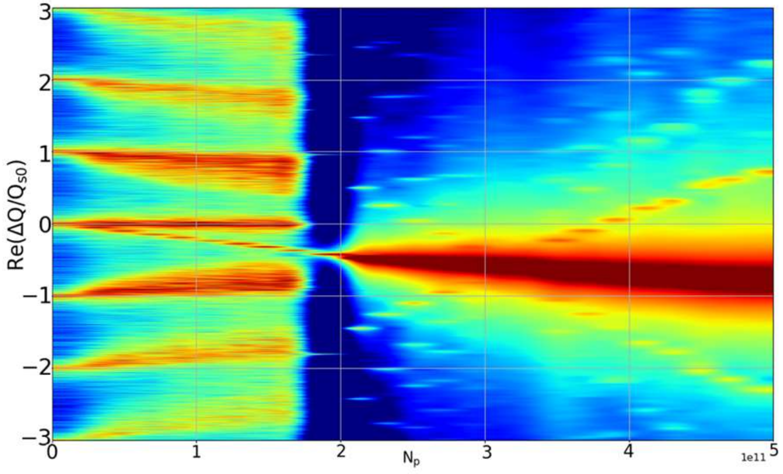


Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP$_{main}$ [cm^{-2}s^{-1}]	5-10 x 10^{34}	1 x 10^{34}
Energy/beam [GJ]	8.4	0.39
Synchr. rad. [W/m/apert.]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

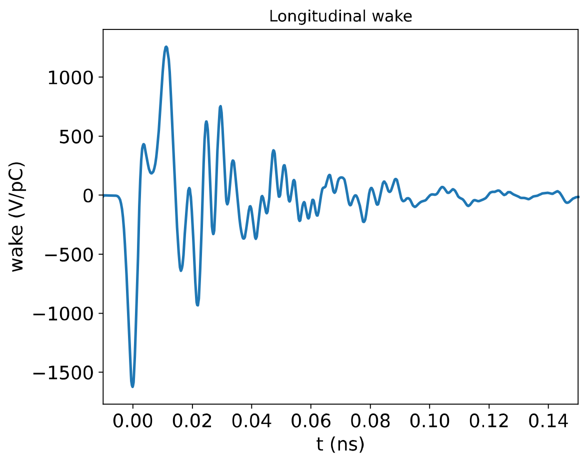
Collaborations with CERN and KEK (Japan) on collective effects and machine impedance model

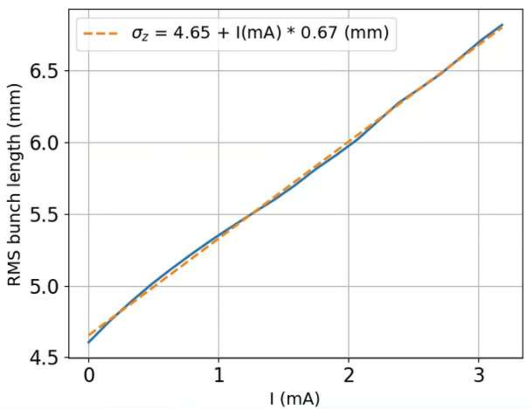
FCC-ee: main sources of impedance budget

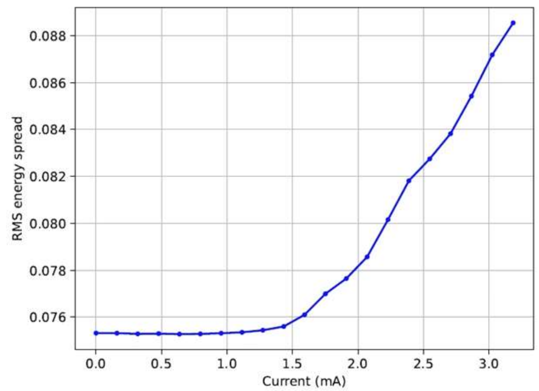
Component	Number	k_{loss} 3.5 mm (V/pC)	k_{loss} 12.1 mm (V/pC)
Resistive wall	97.75 km	214.9	33.1
Bellows	20000	129.3	0.94
BPMs	4000	40.1	4.81
RF cavities	52	17.0	8.76
RF double tapers	13	25.4	2.33
total		426.7	49.94



SuperKEKB longitudinal wake and collective effects



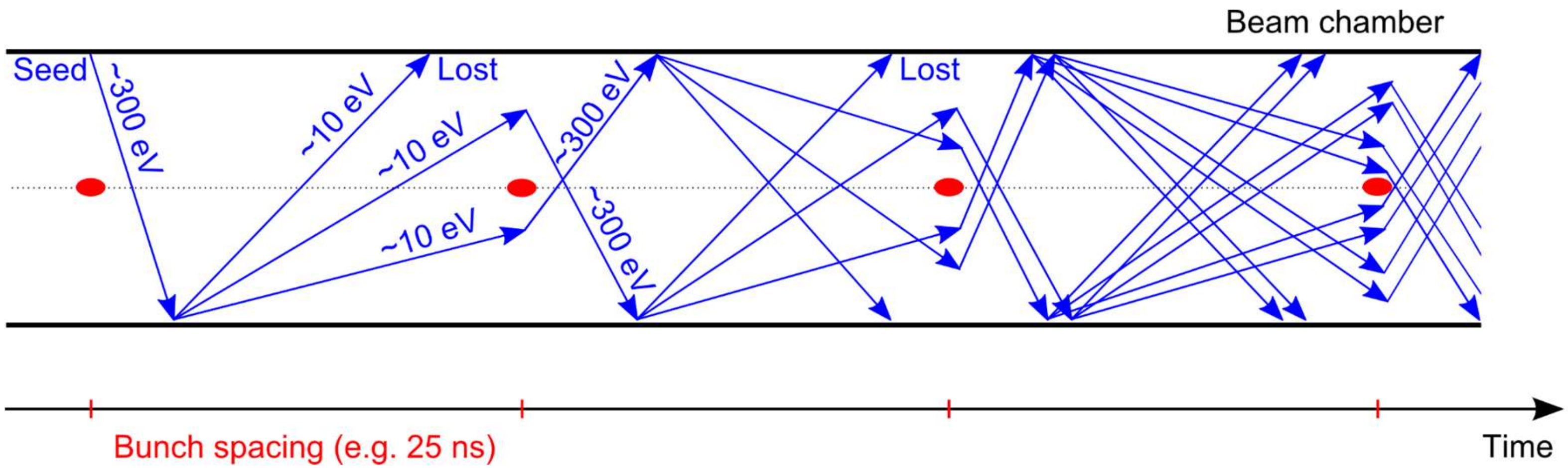




Electron cloud formation in a vacuum pipe

Generation of electrons inside the vacuum chamber
(primary, or seed, electrons)

- Acceleration of primary electrons in the beam field
- Secondary electron production when hitting the wall
- Avalanche electron multiplication



Effects of the electron cloud

The presence of an e-cloud inside an accelerator ring is revealed by several **typical signatures**

- ✓ Fast pressure rise, outgassing
- ✓ Additional heat load (LHC has cold Dipoles)
- ✓ Baseline shift of the pick-up electrode signal

} Machine observables

- ✓ Tune shift along the bunch train
- ✓ Coherent instability
  - ○ Single bunch effect affecting the last bunches of a train
  - ○ Coupled bunch effect
- ✓ Beam size blow-up and emittance growth
- ✓ Luminosity loss in colliders
- ✓ Energy loss measured through the synchronous phase shift

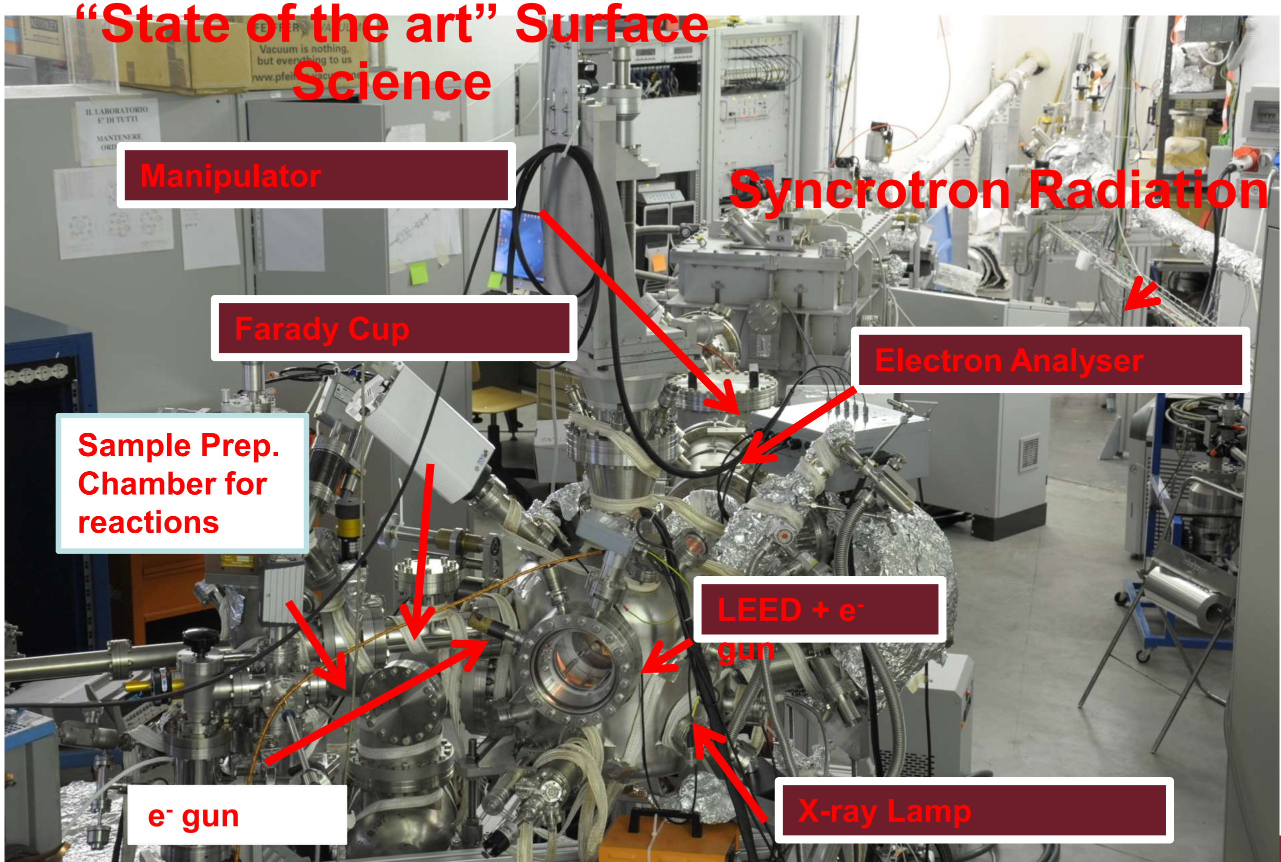
} Beam observables

- ✓ Active monitoring: signal on dedicated electron detectors (e.g. strip monitors) and retarding field analysers

PhD thesis in this research framework
and
in collaboration with CERN and EIC:

Experimental investigation on relevant material properties for FCC & Hi Lumi LHC

- Surface properties of Carbon and Cu Surfaces for HL-LHC (INFN project)
- electron induced Desorption (possibly an EU / INFN Project)
- photo desorption: Synchrotron radiation studies (MoU with CERN/ INFN)



These PhD thesis foreseen experimental studies (with SR and Surface Science techniques) on material properties of interest to the accelerator community.

The interested candidate will work in an international contest, within various international collaborations and will be mainly performing experiments in Frascati National Lab but also in various Facilities around Europe.

Tesi da svolgere presso il Laboratori Nazionali di Frascati dell'INFN
Contact person: R. Cimino (roberto.cimino@lnf.infn.it)

Synchrotron radiation desorption studies of candidates materials to be used for the High Luminosity upgrade for the LHC at CERN

This thesis work will be done in close collaboration with CERN and is finalised to the optimization of the LHC upgrade. New vacuum chambers with integrated tungsten-shielded beam-screen (BS) will have to be installed. A thorough characterization of the surface properties of the BS needs to be done. In particular for the co-laminated copper with different surface treatment for electron cloud mitigation, like amorphous-carbon (a-C) thin film and laser-structured surfaces, with potential applications also for the Future Circular Collider (FCC) design study.

In addition, recent studies have pointed out that the heat load transferred by electron clouds to the LHC arcs' cryogenic systems will remain a subject of concern also in the HL-LHC era, when the number of SR photons will double. A better understanding of the role of synchrotron radiation in the electron cloud built-up process is essential.

Tesi da svolgere presso il Laboratori Nazionali di Frascati dell'INFN

Contact person: R. Cimino (roberto.cimino@lnf.infn.it)

Search of passivating coatings for ultimate performances Vacuum chambers

This thesis work will use the laboratory facilities to study surface preparation/modification apt to produce a vacuum chamber with minimal desorption properties, especially during photon or electron irradiation. The laboratory is equipped with all the technologies and instruments to study thermal, electron and photon stimulated desorption, and some facilities to produce specially designed surfaces and coatings.
Surface morphology modifications, thin film Carbon films, up to Graphene-like coatings, and NEG coatings will be studied to define, at least in principle the way to produce as inert as possible surfaces for Ultra high vacuum applications.

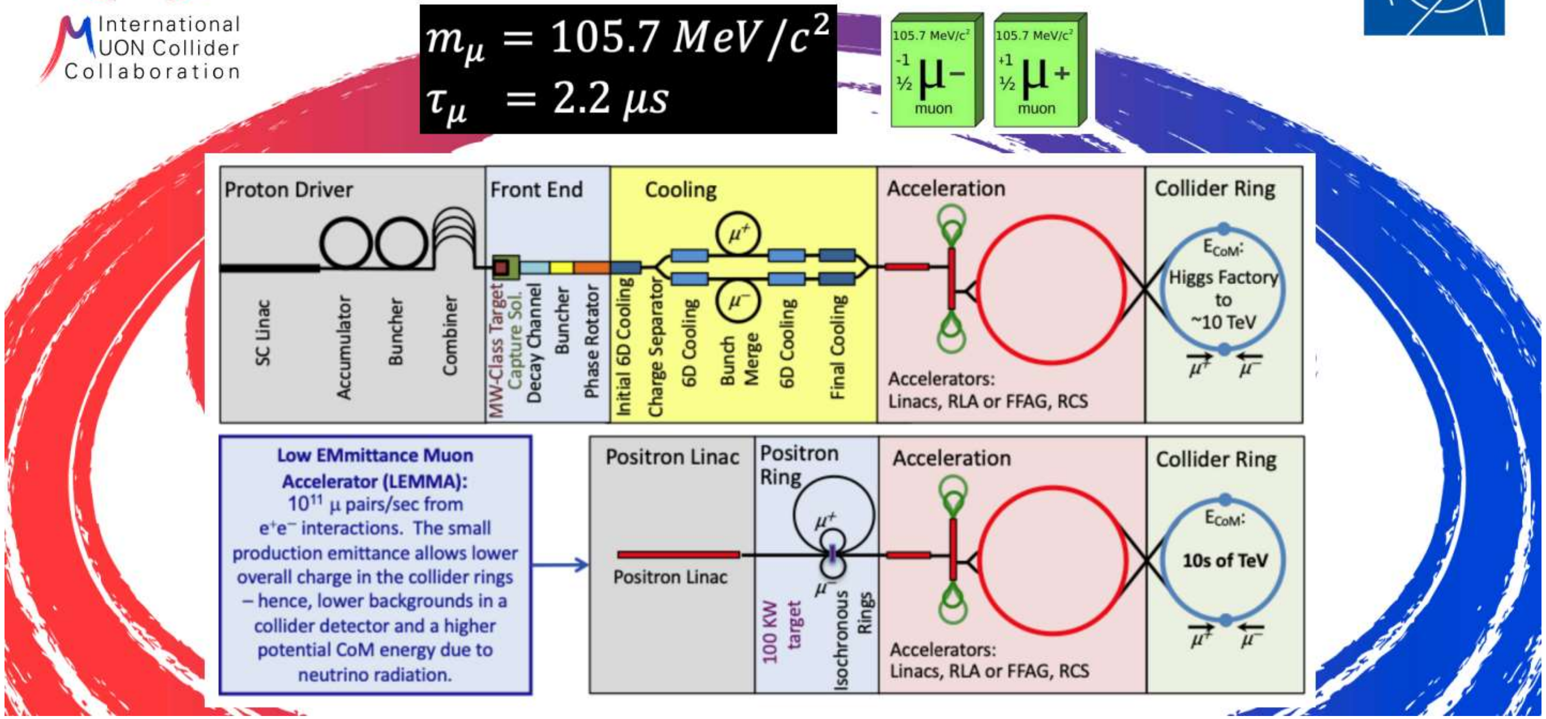
Tesi da svolgere presso il Laboratori Nazionali di Frascati dell'INFN
Contact person: R. Cimino (roberto.cimino@lnf.infn.it)

Collaborations with CERN on beam dynamics and collective effects

Muon Collider Studies

https://muoncollider.web.cern.ch/welcome-page-muon-collider-website

International MUON Collider Collaboration



Collaborations with CERN on beam dynamics and collective effects

International MUON Collider Collaboration

Muon colliders have a great potential for high-energy physics. They can offer **collisions of point-like particles** at very high energies, since muons can be accelerated in a ring **without limitation from synchrotron radiation**

Idea

Protons → target

→ pions

→ muons

→ *μ- μ+* collider

Challenges (of decaying particles)

- Muon production
- Fast muon cooling
- Fast acceleration
- Neutrino radiation

Laser-generated Electromagnetic Pulses per Beam Dynamics (F. Consoli – ENEA)

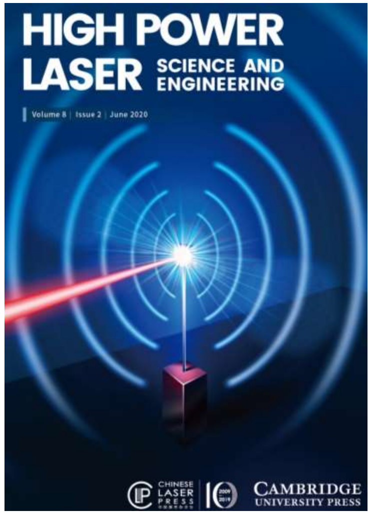
•L’interazione di laser ad alta energia ed intensità con specifici bersagli è un metodo innovativo e molto efficace per l’accelerazione di elettroni e ioni.

•Possibili applicazioni di tali fasci di particelle: medicina, studi sui materiali, fusione nucleare a confinamento inerziale, astrofisica.

•Negli ultimi anni si è osservato un costante incremento delle prestazioni delle facility laser, ed un crescente numero di esse nel panorama internazionale. Le strutture di punta al momento in costruzione includono il laser **ELI L4** (impulsi da 1 kJ di energia, 100 femtosecondi di durata, 10 petawatt di potenza) e il laser **Apollon** (impulsi da 75 J di energia, 15 femtosecondi di durata, 5 petawatt di potenza).

•L’interazione di laser di elevata energia e potenza sui materiali genera inoltre impulsi di radiazione elettromagnetica aventi spettro che va dalle radiofrequenze ai raggi gamma.

•Sono stati osservati campi a radiofrequenza-microonde con valori che superano i livelli del MV/m, con intensità che aumentano con energia e intensità del laser impiegato. Campi così intensi da una parte possono rappresentare un serissimo problema per qualunque dispositivo elettronico presente vicino l’interazione, ed il loro studio è di estrema importanza soprattutto per le nuove facility di accelerazione laser-plasma di nuova generazione, come ELI L4 ed Apollon.



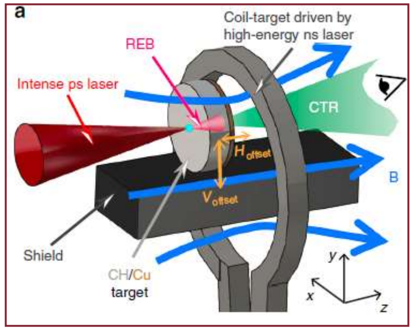
•E’ quindi di capitale importanza poter comprendere appieno i meccanismi sorgente di tali campi, ancora lontani dall’essere stati del tutto definiti e comparati.

F. Consoli, et al, "Laser-Generated Electromagnetic Pulses: generation, detection and mitigation", High Power Laser Science and Engineering Vol. 8, e22, (2020)

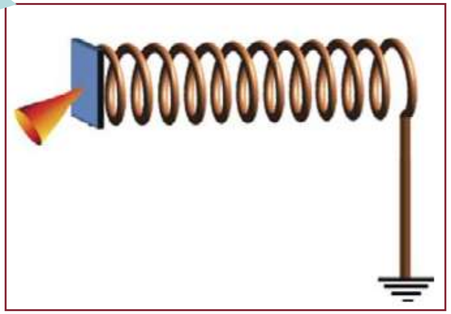
•Campi EMP di tale intensità, ed associate correnti transienti, sono stati invece recentemente impiegati allo scopo di creare:

– campi magnetici transienti dell'ordine del kilo Tesla [2],

– campi elettromagnetici a traveling-wave [3].



•Tali campi si sono dimostrati particolarmente efficaci nel focalizzare un fascio di particelle cariche accelerate da interazione laser-materia [2,3].



•Campi di questo tipo possono essere efficientemente impiegati in strutture di condizionamento (focalizzazione, bunching, chopping) di un fascio di particelle accelerato sia da interazione laser-materia che mediante acceleratori di tipo classico [1-3].

Il campo di ricerca è molto vasto ed aperto. Riguarda

• l'indagine sui diversi meccanismi di generazione EMP, mediante appropriate campagne sperimentali svolte in diverse facility laser e studi teorico-numerici;

• lo sviluppo di metodologie di diagnostica avanzate per tali campi EMP;

• lo sviluppo di metodologie per il condizionamento dei campi EMP e lo sviluppo di strumenti e metodologie di diagnostica dell'interazione laser-materia che abbiano elevata reiezione ai campi EMP;

•lo studio e lo sviluppo di schemi per l'impiego costruttivo di tali campi nei diversi e promettentissimi ambiti di applicazione, con particolare focus verso la beam dynamics.

Il Centro Ricerche Frascati dell'ENEA è molto attivo in tale ambito, ed in particolare ha prodotto recentemente un brevetto internazionale per l'impiego di tali campi in diversi ambiti di applicazione, tra cui l'impiego degli stessi per scopi di beam dynamics.

[1] F. Consoli, et al, High Power Laser Science and Engineering Vol. 8, e22, (2020). [2] M. Bailly-Grandvaux et al, Nature Communications (2018) 9, 102; [3] S. Kar, et al, Nature Communications (2018) 7, 10792